**Final Technical Report:**

**"Optically Triggered, Superconducting Opening Switch"**

**to:**

**Ballistic Missile Defense Organization through the Office of Naval Research**

ONR contract #N00014-92-J-1993 managed by Dr. Gabriel Roy


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## I. ABSTRACT


The advent of high-temperature superconductors (HTS) introduced the possibility of a new class of opening switches.[1] The switches exploit the dramatic change in material properties at the critical temperature, $T_c$, in the HTS materials. The transition to the normal state can form the basis of an opening switch. Since this phase transition is fully reversible, the switch can be operated repetitively. Such devices could switch currents in the range of a few kA with switching time of the order of nanoseconds. We have developed and tested two types of opening switches based on HTS materials: a photoresistive switch and an inductively coupled switch. Each switch was demonstrated at low power levels and subsequently scaled up to power levels corresponding to tens of amperes current interruption.

## II. INTRODUCTION

In an opening switch, current is conducted under normal operation and is interrupted when the switch "opens." The current is then diverted to another path. Opening switches have several applications. However, only recently have advanced opening switches become available. A very interesting area is for flexible power AC transmission systems (FACTS).[2] In order to ensure the proper flow of electrical energy in a complex transmission network, it is necessary to shift reactive elements into and out of the transmission system controlling the phase of the line voltage with respect to the line current. Ideal reactive elements do not consume any real power, but due to deviations from perfect behavior, there is real power loss. Additional losses in the switching circuitry contribute significantly to the total system losses. Significant energy savings and cost reductions can be achieved if those losses are reduced or eliminated. Pulse power presents other applications for opening switches. Opening switches can be used to discharge inductive energy storage systems to provide high power bursts of energy.

Mechanical switches and fuses are classical examples of opening switches. In electric utility applications these devices are used for circuit breakers and current fault limiters. But these devices are limited by several factors including switching speed, lifetime (i.e., the number of switching cycles they can survive), generation of electromagnetic interference, and the need to suppress arcing with environmentally unfriendly materials. For advanced switching applications, these types of devices are not applicable. The only opening switches presently available for advanced applications are variations of the solid-state thrystor, primarily the gate turn-off thrystor or GTO. GTO's are four-layer semiconductors that have a blocking voltage of about 5 kV, and a current rating of 2.5 kA with a forward voltage drop of 2–4.5 V.[3] Thus the primary disadvantage of semiconductor opening switches is the large IV losses in the conducting or closed state. These can be significant because an opening switch is usually closed for a significant fraction of the operation cycle. To make a better opening switch, we must address the weaknesses of the GTO.

The goal of this research was to develop new opening switches based on optically activated thin films of HTS materials such as $YBa_2Cu_3O_{7-\delta}$ (YBCO). Optical activation is attractive because the films exhibit low reflectivity and a high-absorption coefficient over the visible and near-infrared part of the spectrum. This contract focused on the use of a laser to drive the YBCO into the normal state. The optical absorption depth is compatible with the thickness of the high-quality, HTS materials that are presently being grown as thin films. Despite their small cross-sectional area, thin films have very good current-carrying capability and the photo-activated switches should have very fast switching times. The switching times are less than 50 ns because the thermal mass of the thin film is so small. The HTS films have excellent superconducting properties including high transition temperature (>82 K ), large critical currents (>1 MA/cm$^2$ @ 77 K), and high critical magnetic fields (>20 T at near 0 K). These properties were exploited for two different types of switches.

The photoresistive switch, the first type we studied, uses the very high normal state resistivity of these materials. Unlike low-temperature superconductors (LTS), the HTS materials become poor conductors as they rise above the critical temperature. In this type of switch, we simply heat the material above the transition temperature and let the change in resistivity constitute the basis of an opening switch. When illuminated by light at an intensity of 5–10 mJ/cm$^2$, a thin film of YBCO will change from a perfect conductor to a very resistive material. Typically, a 1-μm-thick film, with a length to width aspect ratio of 10, will switch to a resistance of several hundred ohms. A 1-cm-wide film, should be able to carry a current of 500 A to 1 kA. This switch must be operated in a cryogenic environment. The principal advantage of the photoresistive switch, which justifies going to cryogenics, is that it is a fast, high-power, opening switch that can be repetitively triggered and has zero losses in the conducting state. No other switch meets all these criteria. The most likely application of this type of switch is as an element in advanced static VAR (volt-ampere reactive) compensators used to control the power flow in electrical transmission networks.[4]

The inductively coupled switch, the second type we considered, uses the magnetic field screening properties of these materials. The Meissner effect allows a superconductor to behave as a perfect dimagnet.[5] Thus, magnetic flux cannot pass through the material. The switch consists of a thin film of YBCO that isolates the primary and secondary of a transformer. When the film is driven normal with a laser pulse, energy can be transferred from the primary to the secondary. The principal advantage of this type of switch is no mechanical contact is required between any of the three component parts. Each component can be maintained at a different temperature with minimal thermal isolation problems. This property makes these switches particularly attractive for energy extraction from superconducting magnetic energy storage systems (SMES). The primary magnet would be made from an LTS material such as NbSn, but the switch would be an HTS material and the secondary would be a conventional copper coil. The primary can be maintained as a closed loop carrying a persistent current at liquid helium temperatures. Unlike currently operating SMES systems, there is no need to bring the superconducting current out of the cryogenic dewar. This will eliminate continuous thermal losses in the system that are typically greater than 32 kW for μSMES systems that are commerically available.[6] The YBCO thin film can be at a temperature of 20 to 70 K and can be incorporated as part thermal shielding of the primary. Since optical triggering will be used, there is no need to have any wires connecting to the shield. This will further enhance the thermal isolation.

## III. PHOTORESISTIVE SWITCH

To fabricate an opening switch with HTS material, it is necessary to have some method of triggering the switch into the normal state. The transition should be as rapid as possible because the heating of the switch due to the nonzero current-voltage product, IV, can be very large during the transition. Before the transition, the current is large but the voltage is zero and after the transition the current is approximately zero. The method of excitation should also allow for thermal isolation of the switch before it is triggered. In the pretrigger state, the device will be at cryogenic temperatures. Good thermal isolation reduces the load on the cryogenic cooling

system. A method of triggering that is compatible with both of the above points is excitation with short optical pulses. HTS materials are highly absorbing at visible and near-infrared frequencies and have very low reflectivities. Thus, most of the optical energy is coupled into the material. We have constructed and tested low power versions of these devices. The transient electrical response of superconducting films irradiated with 170-ps optical pulses from a Nd:YAG laser were investigated, and a number of parametric studies of the voltage transient that were switched to the load were carried out.[7]

Low-power switches were fabricated from thin films of YBCO. The films ranged in thickness from 0.2 to 1.3 μm. A variety of substrates were used including MgO, zirconia, $SrTiO_3$, and $LaAlGaO_3$. A focused laser beam was used to ablate parts of the film and thereby pattern device structures. The fabricated structure consisted of an "H" with a central bridge region 200 mm wide and 2 mm long.[1] Low-resistance contacts (about 1 Ω) were obtained by evaporating 0.2 μm of Ag on top of the YBCO films. The pads were wire-bonded to the external circuit. The dc-resistive transition of the bridge region of one such patterned film, 0.7 μm thick, is shown in Fig. 1. For the pulse excitation measurements (see Fig. 2), the sample was mounted in a vacuum chamber on a cold finger whose temperature could be controlled from 20 K to 100 K. The switch was provided with a dc-bias current (typically 0.1–100 mA) across two of its legs, and a 50-Ω load resistor across the other two. The device was mounted in a transmission line geometry and the input and output cables were long enough that no reflections occurred in the temporal window of interest. The voltage across the load was measured with either a fast analog or a digital sampling oscilloscope, both with temporal resolution of about 1 ns. The switch was illuminated through a quartz window with 170-ps pulses from a Nd:YAG infrared laser with an energy per pulse of up to 300 mJ and a repetition rate that could be varied from 1 Hz to 1 kHz. Typically the switches were operated at about 50 Hz. The optical pulse was cylindrically focused to overfill the switch. We typically achieved 20% uniformity of the illumination over the active area of the switch.

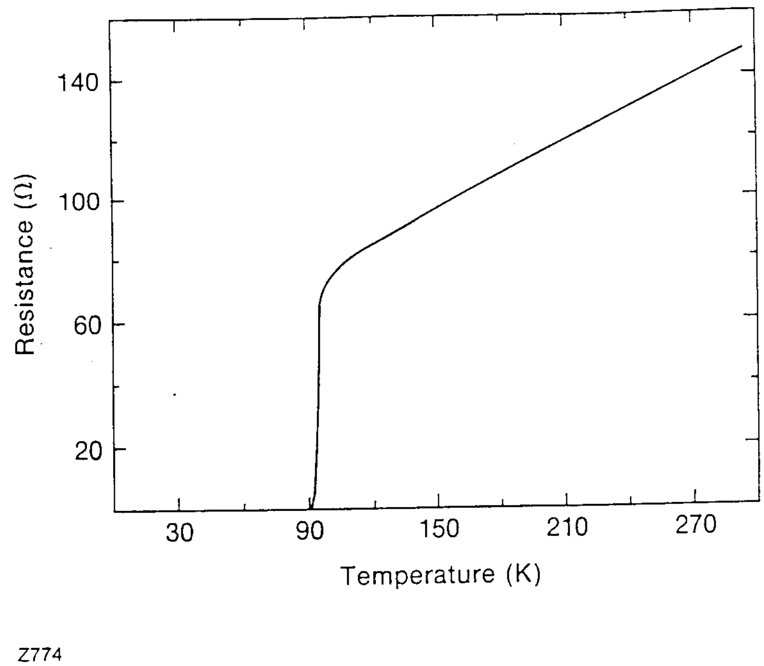


Fig. 1 The resistance versus temperature for a 0.7-μm thick film. The strip was 2 mm long × 0.25 wide.

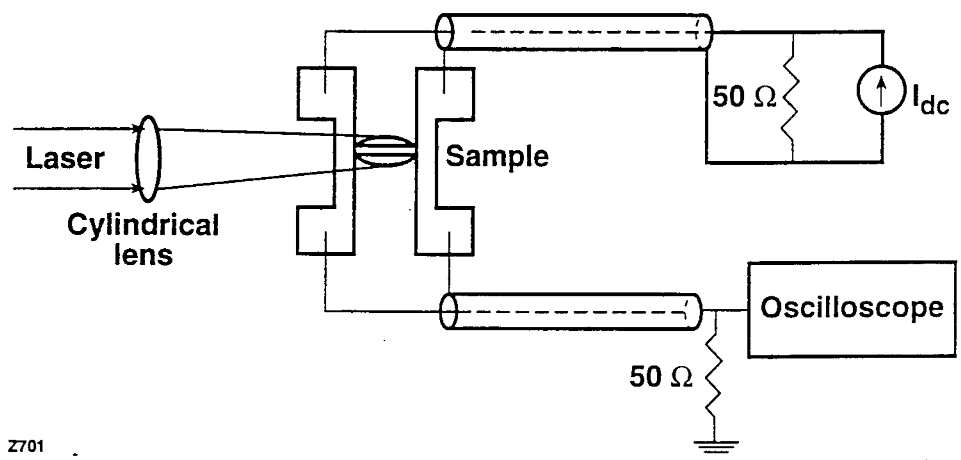


Fig. 2 The experimental schematic showing the laser illuminating the bridge.

The observed signal clearly exhibited two switching mechanisms (Fig. 3). The slower response, which is believed to be bolometric in nature, was preceded by a faster component having a rise time of the order of a few nanoseconds. The slow thermal component had a time lag compared to the optical trigger, which increased with decreasing laser fluence. The dependence of this time lag of the thermal component, called the response time of the switch, on the laser

fluence is shown in Fig. 4. For the same laser fluence, this time lag was found to decrease with increasing bias current. A simulation of the bolometric response, exhibited similar dependence of the response time on fluence and bias current. The faster component, which is synchronized with the optical trigger in time, is not of a thermal origin. At present, the origin of this nonbolometric signal component is not clearly understood. It is not associated with the energy redistribution in the film since such a mechanism cannot account for a sharp recovery followed by a secondary thermal rise. The fall time of this signal component is 5 to 6 ns. In the time period that the nonbolometric part of the signal exists, the optical energy is mostly confined to the front surface of the film suggesting that the signal originates at the surface. It is possibly associated with the kinetic inductance.

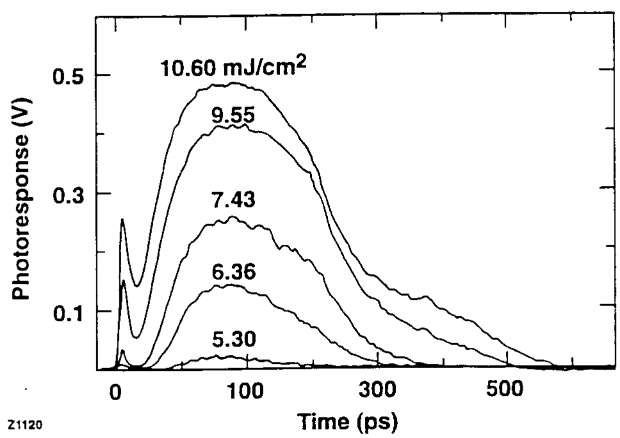


Fig. 3 The bolometric and the nonbolometric switching components in the photoresponse of YBCO thin films for varying laser fluence. The total optical energy used in each case is shown (about 20% of this energy is absorbed by the switch). The central bridge has dimensions 100 μm × 2 mm. Initial temperature is 70 K and bias current is 30 mA.

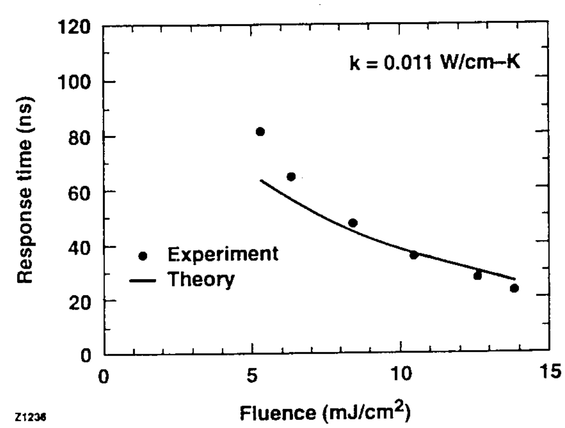


Fig. 4 Thermal response time as a function of laser fluence. The theoretical curve is calculated using the peak intensity of the Gaussian energy distribution.

Variation of the initial temperature of the sample permitted the fast signal to be clearly distinguished from the slow one. When the sample is cooled to a temperature just below $T_c$ before hitting it with the laser pulse, the response time of the thermal component is comparable to the width of the fast pulse. This results in a superposed signal that appears to be a single

voltage pulse with a sharp initial slope followed by a slow "thermal-like" rise. As the sample is cooled to lower initial temperatures the thermal pulse starts moving out in time and the overlapping time interval of the two signals becomes smaller. Finally, at low temperatures the two signals are separated in time. Since this temperature is well below $T_c$ (=84 K), usually less than 60 K, we need a high bias current and/or high laser fluence to perform the switching. At low temperatures the critical current is very high, and a significant amount of optical energy is needed to raise the temperature above the critical temperature.

The peak amplitude of the fast signal decreases with diminishing laser intensity. However its rise time (~4 ns), and fall time (~5–6 ns), were found to be independent of laser fluence, bias current, and initial temperature. There is a minimum fluence for the fast component to exist for any given temperature and bias current. The thermal component has a threshold fluence, corresponding to the minimum energy required to raise the temperature of the film above its critical temperature. The threshold fluence for the thermal component is found to be lower than that for the nonthermal component. When the fluence is between these two thresholds we can observe only the thermal part of the signal.

The fast rise times are somewhat unexpected for samples thicker than 0.5 μm. YBCO has a measured absorption depth (1/e) of 0.17 μm. For thick films, most of the optical energy is deposited in the front surface of the film. The material has a very poor thermal conductivity. Figure 6 shows a simulation where the deposited optical energy decreases exponentially with distance from the surface. Using published values for the thermal conductivity and heat capacity of YBCO, heat equation is solved using finite differences in one dimension.[4] It takes at least 50 ns for the back of the sample to rise above $T_c$. The sample current density was well below $J_c$. Thus, the signal at the load should have taken at least 50 ns after the light pulse to reach its peak. All of the current should have diverted to the superconducting regions and no current would have appeared at the load at times less than 50 ns. Experimentally, the signal was seen to rise in 1 ns. The fast rise time is probably due to redistribution of current in the switch.

The amplitude of the main signal corresponds to thermal heating. The resistance verses temperature curve is measured for each switch. We can calculate the expected temperature rise for a given amount of optical energy and use that to determine the resistance of the switch. From a simple circuit model, the signal voltage can be predicted. As the operating temperature of the switch is decreased, more optical energy is needed to heat the switch above $T_C$. There should be a threshold energy necessary to drive the switch normal if the mechanism of excitation is heating. A nonbolometric mechanism may not have a threshold. Figure 5 shows the measured signal amplitude plotted against the optical intensity at various temperatures. There is clearly a threshold that increases with decreasing temperature. The slow decay time is also indicative of heating. If the thermal coupling between the cold finger and the switch is reduced, the decay time will become longer.

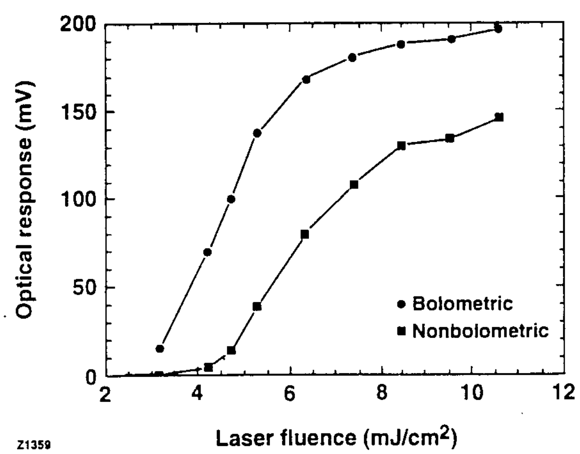


Fig. 5 The peak of the slow signal shows saturation at high intensity. There is a threshold intensity that increases with decreasing temperature. The fast nonbolometric component does not show a threshold.

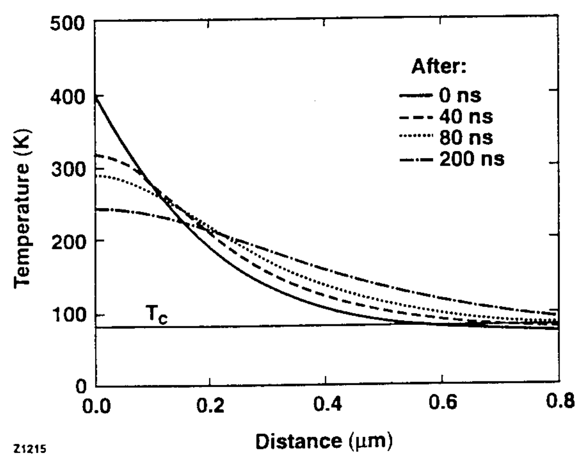


Fig. 6 Simulation showing that the heat pulse takes 50 ns to raise the entire film above $T_C$.

We constructed a test bed that allows us to operate the photoresistive switch at currents as high as 100 A. A 10-mm-wide, 4-mm-wide, 0.5-μm-thick film was used as the switch. A 0.56-mΩ load was in parallel with the switch. Flowing liquid nitrogen provided the coolant. In this configuration the switch temperature could be reduced to 80 K. At this temperature, the

critical current was exceeded at 30 A. This level was the maximum at which we observed optically activated switching into the load resistor. The rise time was 5 ns and the thermal recovery time was about 300 ns. These experiments demonstrated a hundred-fold increase in switch current. Further increases are anticipated with lower temperatures and films having higher critical-current densities.

The design of the switch was relatively simple (Fig. 7). Two copper blocks, separated by a tube 4 mm long made of Kel-F, are connected by three high-resistivity Nichrome pins. These pins constituted the 0.56-m$\Omega$ load. Nichrome (80 Ni 20 Cr) rods were chosen to be used as the parallel load because of their high resistivity (108 $\mu\Omega$-cm). The three rods were 0.4 cm long and 0.18 cm in diameter. When connected in parallel, they had a resistance of 0.563 m$\Omega$, compared to 5–10 $\Omega$ for a typical YBCO sample in the nonsuperconducting state. Electrically isolated bolts clamped the assembly together. Copper tubes, which extended from both blocks along with the Kel-F tube, carried the liquid nitrogen coolant. The copper tubes also acted as the primary current leads. The dual purpose copper tubes allowed us to transfer the high current into the cryogenic environment with minimal thermal loading. The apparatus was housed inside a vacuum chamber to prevent condensation on the sample and heating from the environment. Copper tubes extended outside of the vacuum chamber using insulating bushings.

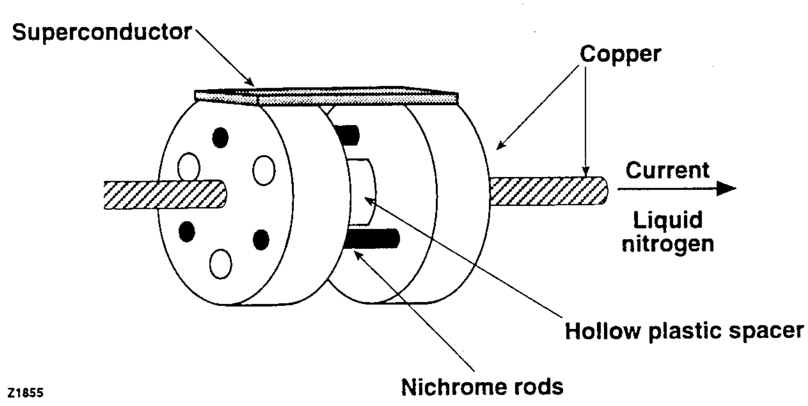


Fig. 7 A simple switch design allowed us to achieve high current switching with the photoresistive switch.

The superconductor was clamped on top of the blocks, connected in parallel to the wires. A YBCO thin-film superconductor sample 1 cm$^2$ × 0.5 $\mu$m thick deposited onto an $LaAlO_3$

substrate half a millimeter in thickness was used.[3] Silver contact pads, 0.5 μm thick, 0.4 cm wide, and 1.0 cm long, were first evaporated onto the film. The sample was then annealed in flowing oxygen at 450°C for about 1/2 hr to reduce the contact resistance and improve adhesion of the silver onto the sample. The sample itself was placed face down on top of the copper blocks on a section that was milled flat. Indium sheets were used to improve the electrical and thermal contact between the YBCO and the copper blocks. The superconductor was secured with screws and copper clamps. A high speed cable was connected across the switch to measure its voltage.

The resistance versus temperature curve of the switch was measured at low currents ranging from 0.1–1.0 A. The chamber was pumped out using a cryopump to a pressure of 40 μm of Hg or less. While running a current through it, the liquid nitrogen was flowed through the copper tubes to cool the switch. The switch attained superconductivity at 84 K. The coldest temperature obtained was around 80.5 K. Once the superconducting state was reached, the current through the switch was increased. The laser was fired onto the sample to test to see if it would switch. An oscilloscope was used to measure the voltage across the switch and detect the switching signal. Actually, the response detected by the oscilloscope was generated by a current flowing through the parallel load.

The laser pulse was supplied from a Nd:YAG laser. The pulse was fired at a rate of 4 Hz and had a duration of 180 ps. The beam size was expanded to approximately 1 cm in diameter. Each pulse delivered between 12–14 mJ of energy. The oscilloscope averaged the response from multiple triggers before displaying a signal. Signals were recorded for currents up to 70 A. Signals were also taken, while the laser was blocked to serve as a baseline for the noise level. This was later subtracted from the switching signal to produce a cleaner plot.

The resistance of the film while in the normal state was about 6 Ω. As the resistance of the sample in the normal state was significantly higher than the Nichrome shunt, it posed an insignificant effect on the resistance of the overall parallel circuit. However, when the YBCO was superconducting, all the current went through the sample. The detected voltage for the

switch at room temperature (nonsuperconducting state) varied from 0.104–1.076 mV for 0.1–1.0 A of current, respectively.

The measured signals all showed a rise time of 10 ns or less. It seemed that kinetic inductance dominated the rise-time signal. The fall time had a much slower decay due to thermal conduction. The fall-time was about 200–300 ns (Fig. 8). The measured peak voltage when

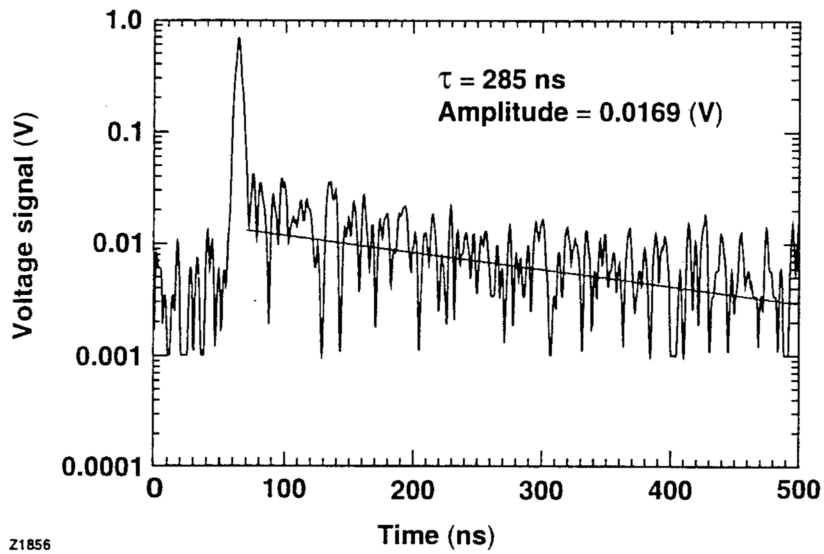


Fig. 8 The response of the high-current YBCO switch at 15 A bias and 14-mJ optical energy. The parameters describe the fit to the resistive tail.

switched was higher than from a simple resistive model. The explanation for the larger signal was the series inductance associated with the Nichrome rods. When switched, the current was redistributed to the three rods and the impedance was dominated by a high inductance on the nanosecond time scale. The estimated value of 0.7 nH is reasonable for the size of the wires used. The maximum current the switch was tested at was 70 A. However, the switched signal was sitting on a dc background indicating that the critical current was exceeded and the sample was in a mixed state. The dc component disappeared at 25 A at a temperature of 80.5 K. Reducing the temperature by a few degrees kelvin should significantly improve the current handling capability of the switch. The critical current increases with temperature:

$$J_c(T) = J_{co}\left[1-(T/Tc)^4\right]^{1/2} .$$

Due to limitations on our cooling system, the operating temperature was only 3 K below the transition temperature of the superconductor. The critical-current density, which placed the upper limit on the switched current, can probably be increased by an order of magnitude if the operating temperature is decreased to about 70 K. Lower temperatures can be achieved with either a closed-cycle refrigerator or liquid He cooling.

## IV. INDUCTIVELY COUPLED SWITCH

Screening currents in a superconducting thin film will exclude a perpendicular magnetic field, produced either by a coil or a magnet. When the film is driven into the normal state by a fast optical pulse, the screening currents decay, allowing flux to enter. The process of flux entry can be observed by measuring the induced voltage across a coil closely coupled to the film. A switch design and theoretical analysis of current redistribution in optically irradiated YBCO thin films are discussed in this section.

Preliminary experiments confirmed the inductively coupled switching. Copper coils were used for both the primary and secondary coils. The film, sandwiched between the coils was placed inside a temperature-controlled cryostat cooled by a closed-cycle refrigerator (Fig. 9). The coils were made from insulated 40 G copper wire. Since the mutual inductance drops drastically with the separation between the coils, flat, washer-shaped coils were used. Thin YBCO films, with thickness varying from 500 to 800 nm, were deposited on heated MgO substrates (1 cm × 1 cm) by RF magnetron sputtering.[8] The film surface was protected by a 12-mm Teflon™ sheet, and two identical coils were placed on either side of the sample. The inner diameter of each washer-shaped coil was 3 mm and the outer diameter was approximately 6 mm, depending on the number of turns. A 100-turn coil had an inductance of 50 mH.

The switch was mounted on the cold finger inside an optical-access cryostat. Light from a Nd:YAG laser illuminated the film. The voltage across the secondary coil was measured above and below $T_c$ using sinusoidal input. The output voltage above $T_c$ was found to be more than 20% of the input voltage indicating 20% coupling for identical primary and secondary coils. As

the sample was cooled through the transition, the coupling dropped from 20% (which was found to be the same at room temperature and at the onset of transition) to less than 1% in a temperature range of 2 K. This indicates that at least 95% of the flux was screened by the superconducting film. We believe that most of the detected leakage was due to electro-magnetic pickup rather than magnetic induction.

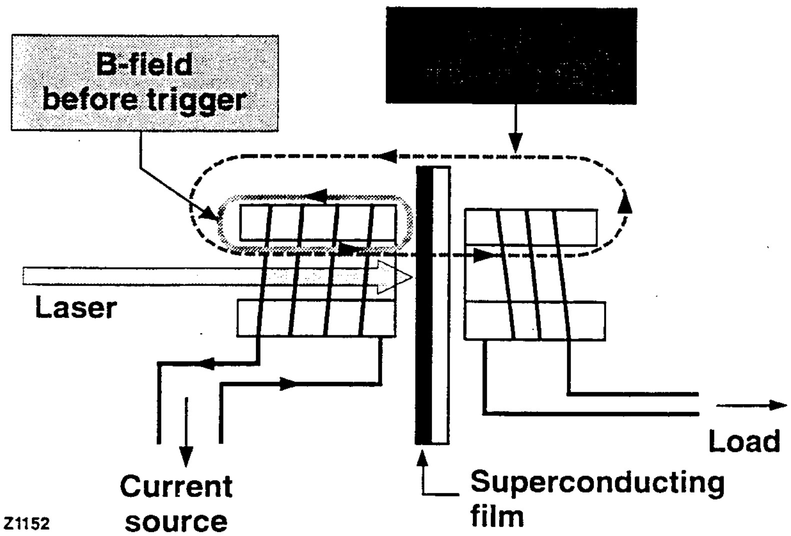


Fig. 9 Superconducting inductively coupled opening switch.

Instead of a dc current, 5-ms pulses at low duty cycle were applied to avoid joule-heating the primary. The current pulse was synchronized in time with the laser pulse such that each laser pulse arrived at the center of a current pulse. The primary current pulse introduces flux in the primary for a period of 5 ms and then turns it off, producing a positive and a negative voltage pulse across the secondary load corresponding to its leading and trailing edges. Above $T_c$ these voltage pulses are indicative of the amount of flux coupled to the secondary coil and can be used to compare with the optical response. The current pulse is long enough so that the optical effects take place during a time when the primary current produces a constant (dc) flux. When the film was cooled below $T_c$, the amplitude of these pulses was greatly reduced because of flux screening by the superconductor. We observed a voltage pulse at the load when the switch was irradiated with a laser pulse. The optical heating caused a transition of the film to the normal state and the flux coupled to the secondary coil. The amount of flux coupling varied with laser

fluence (Fig. 10). By varying the laser fluence we were able to vary the amount of heating of the film. The coupled flux (and hence the induced voltage) increased as the film was heated through the transition regime before saturating. The saturation indicates that the film was fully in the normal state. The maximum induced voltage for optical triggering is approximately 400 mV. The rise times are 40 to 60 ns. We have found no evidence that the superconducting film degrades with repeated operation. The switches were triggered by 150-ps pulses from a Nd:YAG laser at repetition rates up to 1 kHz. High repetition rates are limited by the switch recovery time, which in this case depends on how fast the heat can be extracted from the film.

We designed and built a cryostat operating within the warm bore of a superconducting magnet. This cryostat allows us to test the inductively coupled superconducting switch in magnetic fields up to 4 T and temperatures ranging between 10 and 100 K. High-field switching is desirable because the energy density is higher and the entire system will be more compact. The configuration of our switch is shown in Fig. 11. The superconducting magnet serves as the primary coil, while two superconducting films (switch) are placed on either side of the secondary coil.

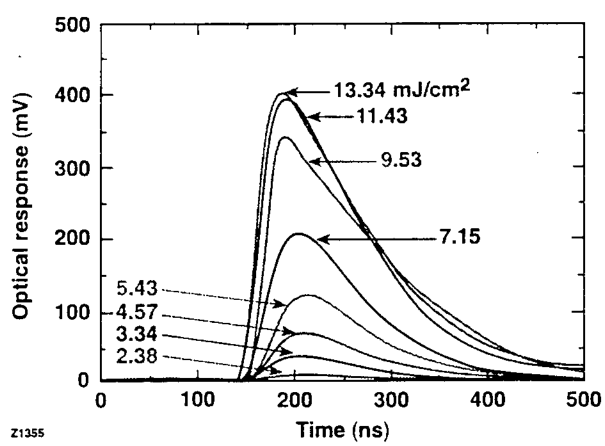


Fig. 10 The inductively coupled switching shows a saturated response as the intensity increases above 10 mJ/cm$^2$.

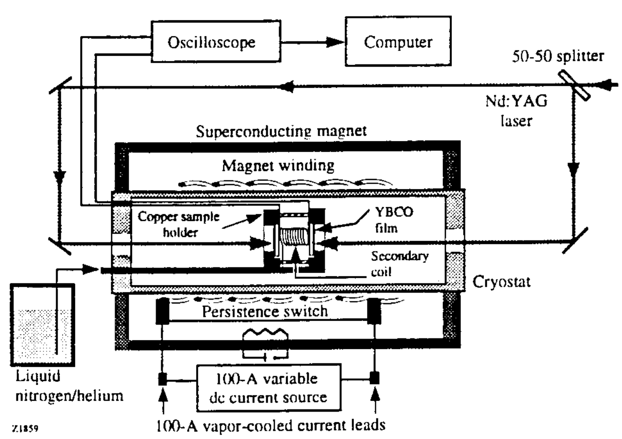


Fig. 11 The high-field experiments were performed with a superconducting magnet acting as the primary coil. The switch is placed inside of a cryostat cooled by liquid nitrogen or helium.

If the applied field, which is perpendicular to the film surface, is below the lower critical field ($H_{c1}$) of the superconductor, the superconductor is in a reversible Meissner state. It will initially screen the flux produced by the magnet from coupling to the secondary coil and allow the flux to move in as it is driven to its normal state by heating with a laser pulse, resulting in a voltage pulse across the secondary. As the film cools down to its superconducting state, it will expel the flux. A repetitive switching can then be performed with a train of laser pulses.[9] If the applied field exceeds $H_{c1}$, however, flux will still be excluded from the superconductor up to a certain field, depending upon the critical-current density of the film. Beyond that only a partial flux exclusion will take place as the screening currents in the superconductor will arrange themselves in a manner to exclude flux from the center of the film. Single shot switching can still be performed under these conditions, allowing the excluded flux to couple to the secondary. As the film cools down, however, it will no longer expel the penetrated flux. The thin-film geometry produces a large demagnetization factor that causes peaking of the magnetic field at the edges of the film. Therefore, even when the applied field is less than $H_{c1}$, some field penetration takes place at the edges.

In order to understand the motion of flux inside the superconductor following its transition into the normal state, we must analyze the distribution of screening currents and magnetic fields. We must also investigate the temporal variation of the flux in the secondary coil, which is coupled inductively to the superconducting films.[10] We first calculate the current and field distribution in a film of thickness t, shaped like a circular disk of radius R, for a given externally applied field ($B_{ext}$) and critical-current density ($J_c$) by dividing the disk into a set of n concentric circular strips of equal width. Starting from the current density distribution J(r), required for complete flux exclusion inside the film, the $J_c$-limited distribution is calculated iteratively. At each step of the iteration the field is allowed to penetrate from the edge by the width of one ring more than the previous step. If the field penetrates to a radius a, $J(r < a)$ is recalculated so as to make the region $0 < r < a$ flux free and $J(r > a)$ is set equal to $J_c$. For a

single film and field-independent critical current our results match closely with the analytical expression given by Mikheenko and Kuzovlev[11] (Fig. 12).

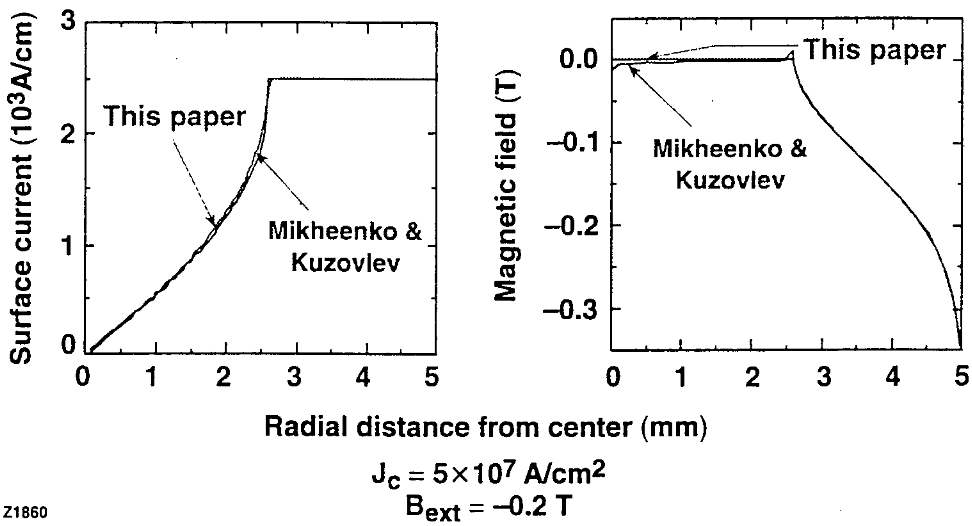


Fig. 12 Comparison of (a) $J_c$-limited surface current and (b) z-component of the magnetic field calculated by the numerical technique described in this paper (solid) and the analytical expression obtained by Mikheenko and Kuzovlev (dashed). In both cases a constant critical-current density of $5.10^7$ A/cm$^2$ and an externally applied field of –0.2 T are assumed.

We then proceed to calculate the temporal evolution of current distributions in the two films and the secondary coil. This is done by treating each ring in the two films and the secondary coil as (2n + 1) circuits. We then solve a set of linear equations of the form $[L]d[I]/dt + [R][I] = 0$, where [L] and [R] are matrices of dimension $(2n = 1) \times (2n + 1)$ and [I] is a column vector. The diagonal elements of [L] are the inductances of each circuit, and off-diagonal elements are the appropriate mutual inductances. [R] is a diagonal matrix with elements equal to the normal-state resistances of the circuits. The elements of [I] represent the current in each circuit. Using this analysis we calculate the current in the secondary coil as a function of time. Figure 13 shows the result of this calculation. The matrix formulation of the problem enables us to take advantage of the computationally efficient matrix manipulation tools in commercial softwares like MATLAB. The numerical method discussed above can easily incorporate additional details,[3] e.g., field-dependent critical-current densities $J_c(B)$, and field-dependent superconducting flux-flow resistances.

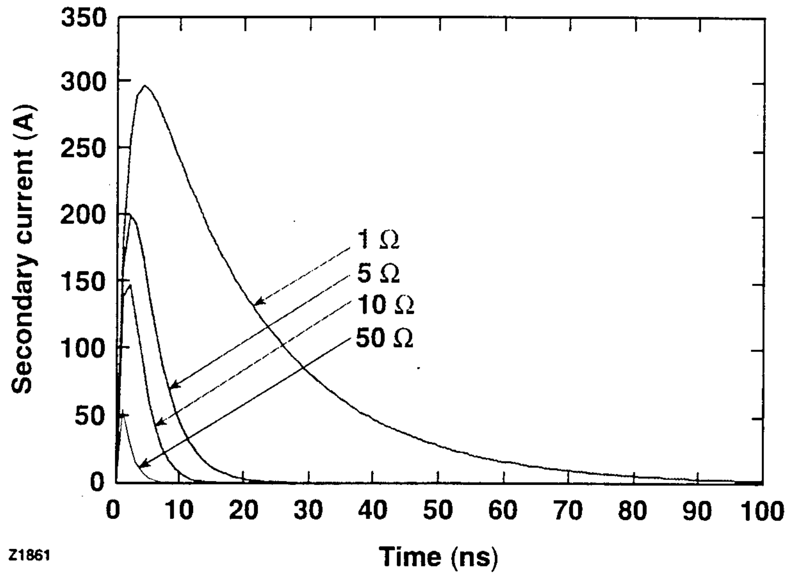


Fig. 13 The simulated current pulse produced at a single-turn secondary coil for different values of resistance ($R_s$). Two identical, 1-cm-diam, 500-nm-thick, disk-shaped superconducting films with $J_c = 5.10^7$ A/cm$^2$ are placed on either side of the secondary coil at a distance of 1 mm. The externally applied field ($B_{ext}$) is −0.2 T.

In our first design the secondary coil consisted of a multiturn copper winding wound around a circular alumina disk (2-mm thickness, 5-mm diam) and impregnated with insulating dope to protect it from electrical breakdown. The coil was then placed inside a 2-in.-thick piece of Teflon™ and fixed in place using epoxy resin. The Teflon™ piece provided a flat surface to support the film. This precaution is necessary because of the magnetic force on the film when the magnet is charged. The sample holder consisted of two circular copper disks (2-in. diam) with square windows (1 cm × 1 cm). The films, placed on either side of the secondary coil were supported by the copper disks and were 500 nm thick on $LaAlO_3$ substrates.

The experiment was conducted as follows. The sample was first cooled by liquid nitrogen or helium to the desired temperature. The magnet was then charged using the current programmer at a ramp rate of 0.1 A/s. The persistent switch heater current was 60 mA supplied by a constant current source. After the desired level of current was established in the magnet, the persistent switch heater was turned off, allowing persistent current to flow through the magnet. The magnetic field was measured using a Hall probe and a gaussmeter.

With the magnet charged, the switch was illuminated by the laser. The YBCO films screening the secondary coils were driven normal by this laser irradiation allowing flux to penetrate. A secondary voltage (of negative sign) appeared across the load. The voltage was found to decrease exponentially with subsequent shots (Fig. 14). The magnet was then

discharged by heating the persistent switch. Driving the films normal again expelled the trapped flux, and we observed the corresponding secondary voltage signal (of positive sign). As before, this voltage decreased exponentially with subsequent shots (Fig. 14). In both cases the voltage as a function of the shot number (n) was found to closely fit the relationship $V(n = 1)/V(n) = e^{-0.6}$. Charge and discharge signals were observed up to a magnetic field of 3 T at a temperature of 27 K. At liquid nitrogen temperature, however, voltage signals were observed up to only 0.4 T.

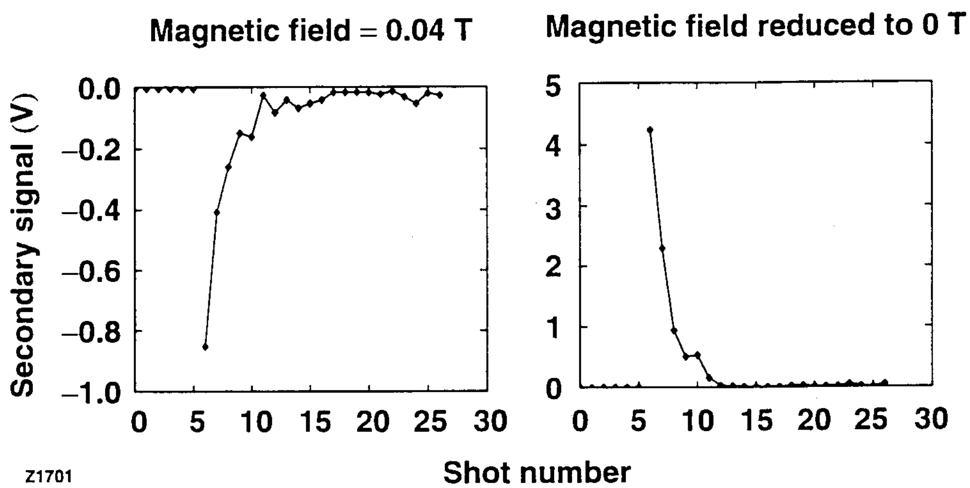


Fig. 14 For a multiturn secondary coil, the secondary voltage signal decreases exponentially with laser shots.

The multiple voltage signals indicate that several laser pulses are required to complete the process of flux entry (or exit) from the films. A possible reason for this is the high secondary coil inductance that impedes rapid flux motion. Therefore, we replaced the multiturn secondary coil with a single-turn inductor patterned on a printed circuit board. We repeated the experiments at liquid nitrogen temperatures and observed only one (occasionally two) voltage pulse at the secondary coil.

Figure 15 shows a comparison of the experimentally observed secondary voltage signal at an applied field of −0.05 T, with the one obtained with the theoretical analysis described in the previous section. The agreement between the two signals validates our theoretical analysis.

The variation of secondary voltage signal for different laser energies is shown in Fig. 16. For lower laser energies, the whole film is not heated above the transition temperature instantaneously. The 500-nm film thickness is greater than the optical penetration depth

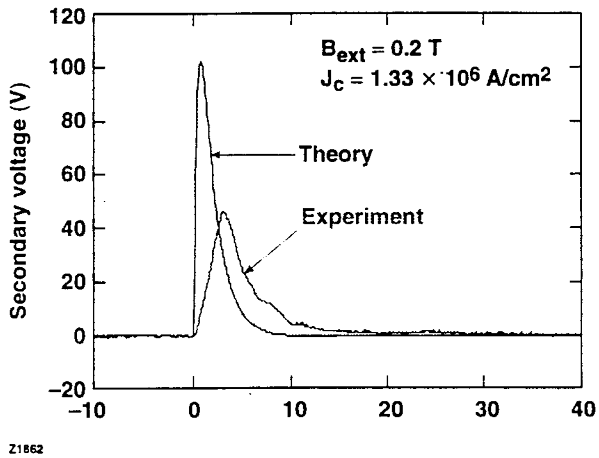


Fig. 15 A comparison of experimentally obtained secondary voltage with the simulated voltage pulse, representing the same flux. The experiment was carried out at 12.4 K in a 0.2 T field with 8 mJ of optical energy.

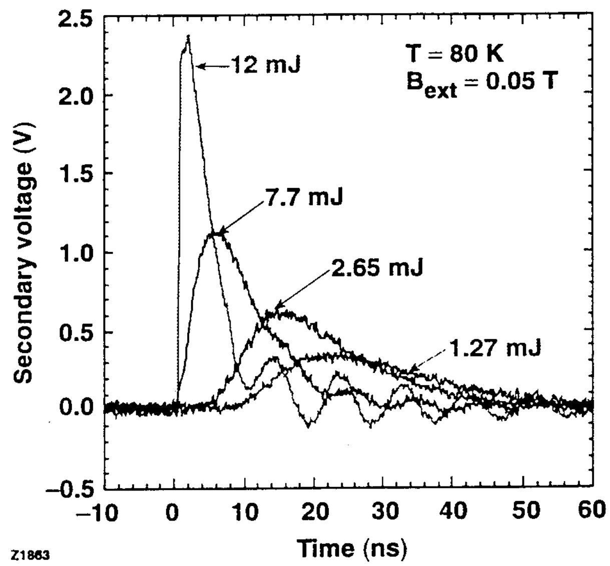


Fig. 16 The speed of flux motion depends on the incident laser energy. For lower laser energy, the bottom part of the film remains superconducting for a while, impeding the motion of flux. The film was a 1-cm-diam disk with a 500-nm thickness in an external field of 0.05 T.

(120 nm), and consequently the top part of the film absorbs most of the energy when the laser pulse is incident on the film. The heat then diffuses through the thickness of the film and eventually heats up the entire film.[12] If we divide the film into several layers along the thickness, the bottom layers will remain superconducting and carry the screening currents even after the top layers become nonsuperconducting. These screening currents continue to exclude flux and slow down the motion of flux. Since the secondary voltage is the temporal derivative of flux, the peak voltage goes down and rise and fall times increase with the decrease in laser fluence. However as shown in Fig. 16, the time integral of the secondary voltage pulse, representing the total flux that has moved in the film (or out of the film), is the same for pulses triggered by laser irradiation of varying intensity. Therefore, we can conclude that higher laser fluence will give rise to faster

signals with higher peak voltage. The energy (E) delivered to the load is given by $E = 1/R\int V^2(t)dt$, where R is the load resistance and V(t) is the voltage across the secondary. For the same flux, $\Phi = \int V(t)dt$, a faster signal will deliver higher energy in the load. At lower temperatures, the critical-current density is higher, and the voltage signal is expected to be larger. The switch can then be used to extract energy more efficiently from the source circuit, as suggested by our theoretical analysis.

In a superconducting magnet operating in the persistent current mode, the conserved quantity is the total flux ($\Phi$) not the current (I). The energy stored in the system is given by $E_{stored} = \Phi^2/2L_{eff} = L_{eff}I^2/2$. $L_{eff}$ is the effective inductance of the system. In the absence of any flux screen inside the magnet, the effective inductance is the self-inductance ($L_M$) of the magnet winding. When an HTS flux screen is placed inside the magnet, the effective inductance of the system is reduced because the HTS changes the field configuration within the magnet by excluding the magnetic flux around it. In our energy extraction scheme, this is the initial state. When the HTS film is switched to the normal state it no longer excludes the flux, and the stored energy is reduced. Therefore, the extracted energy ($E_{ex}$), the difference in stored energy before and after switching, is given by $E_{ex} = \Phi^2/2L_{eff} - \Phi^2/2L_M = (L_M - L_{eff})E_{stored}/L_M$. The extracted energy is related to the amount of flux exclusion by the HTS film in its superconducting state. The value of $L_{eff}$ becomes smaller if the volume of flux exclusion ($V_{excl}$) increases. This can be achieved by using films of larger area or multiple films placed at different locations inside the magnet. For a given magnetic field, B, $E_{ex}$ is given by $B^2V_{excl}/2\mu_0$. $V_{excl}$ is of the order of $4\pi r^3/3$, where r is the radius of the film. The exact value of $V_{excl}$ depends on the value of magnetic field and critical-current density of the film. In the optimized configuration a number of HTS switches placed inside the magnet will exclude a significant fraction of the volume of the magnet. Preliminary estimates suggest that more than half the stored energy can be extracted by the use of multiple switches as discussed in the next paragraph. If we try to fill up the entire volume of the magnet by placing multiple switches, the bending of magnetic field around each film will result in very high flux densities between the films. In that case the films

will no longer be able to exclude the entire field, and the volume of exclusion around each film will shrink.

In a current-multiplication circuit using programmed inductive elements (PIE), storage inductors are charged in series and discharged sequentially in stages that are connected in parallel with the load through a set of isolating closing switches.[13] This circuit can be used to deliver a large load-current using switches that are rated at a fraction of that current. The most important constraint in such a circuit is the synchronization of the opening switches with the closing switches. If the opening switches in this circuit are not triggered within a short temporal window, transient high current or voltages will catastrophically destroy the circuit elements. Optical triggering provides accurate timing. The optically triggered inductive opening switch will be suitable in circuits with such constraints. The contactless arrangement of our switch is specially suited for applications such as energy extraction from SMES though there are some unresolved problems. Self-heating of the film can be a problem as a fraction of the extracted energy gets dissipated in the film. In order to get better flux screening, we need higher currents in the film, which can be achieved by increasing both the thickness and the critical-current density. However, for thicker films uniform heating through optical irradiation is not possible; this would mean a slower response. The main application of SMES is as a backup source of energy to be delivered to the load in a crisis situation. If an opening switch is placed in series with the magnet winding, the finite closed-state resistance of the switch results in a continuous loss of energy while the system is idle. A contactless switch will solve this problem.

A longer term goal for the project is to operate several of these switches in parallel. Our measurements have shown that some flux gets trapped in the film after optical activation. After about ten shots, energy transfer ceases. The external magnetic field must be reduced to zero for the switch to fully recover. A commercial unit will require several switches filling the volume encompassed by the magnetic field. Activating all of these switches should deplete the magnetic field and provide an automatic reset

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**6. Degrees Granted (name, date, degree):**

Paul Ballentine, Jan. 1994, Ph.D. Electrical Engineering

## OTHER SPONSORED RESEARCH

1. "Photo-Assisted Vortez Depairingin Thin Superconducting Films"
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